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Comparative Analysis of Single Stage and Dual Stage PV Based Generation System for Pollution Reduction in Asian Nations

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Abstract: The growing need for sustainable and clean energy solutions has elevated photovoltaic (PV) systems to the forefront of competitive options. In order to evaluate the performance and viability of single-stage and dual-stage single-phase PV voltage source inverter systems within the context of renewable energy, this study undertakes a thorough comparative analysis. MATLAB Simulink has been used to run the simulations, and the results produced show that the selected configurations are robust and closely match theoretical expectations. The study explores the subtle distinctions, benefits, and drawbacks that come with single- and dual-stage systems. By extensively evaluating the consequences on system stability, grid synchronisation, and power quality, useful insights emerge. The simplicity and efficiency of the single-stage system are demonstrated by the direct connectivity between the PV MPPT output and the inverter. In contrast, the dual-stage system addresses the issue of low PV output voltage by incorporating a boost converter with an MPPT algorithm, albeit at the expense of more parts and complexity. The research described here adds a great deal to the current discussion on PV system optimization. The study notably clarifies methods for improving dependability and efficiency in applications involving renewable energy. With the increasing worldwide trend towards sustainable energy, it is critical to comprehend the subtle dynamics of various PV setups. In addition to offering a comprehensive grasp of the complexities involved in single- and dual-stage single-phase PV voltage source inverter systems, this research paves the way for future developments in the planning and execution of effective renewable energy solutions especially for Asian nations that still rely on coal-based power plants. Increased contribution of solar based electricity generation will lead to a significant drop in pollution contributed by the ash and gases released by thermal power plants that employ fossil fuels. The ultimate goal of this study is to provide information to stakeholders in the renewable energy industry so that they may make more informed decisions and create PV systems that are both sustainable for the environment and efficient for the utility.

Key words: Asian nation, environment, pollution, renewable, sustainable.

Introduction

Photovoltaic (PV) systems have become a major contributor to the domain of sustainable energy solutions since they provide the possibility of clean and renewable power generation, thereby reducing pollution. With the increasing emphasis on lowering carbon footprints and switching to more environmentally friendly options, PV systems' efficiency and dependability are critical. Asian countries, specifically India, are heavily reliant on

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coal based thermal energy production. This method of production of energy is detrimental to the environment in many ways. India's coal-heavy electricity system is the world's third largest and a major emitter of air pollution and greenhouse gas emissions (Sengupta et al., 2023). PV systems, coupled with voltage source inverters can be a reliable source of energy for the future as they are non-polluting and have zero emissions. This study aims to compare two different configurations of PV-based setups. The single-stage system offers a simple method of power conversion because of its direct connection between the PV MPPT output and the inverter. On the other hand, the dual-stage system adds a boost converter, which adds another layer and solves the problem of low PV output voltage. The goal of this additional complexity is to improve overall system performance; however, a thorough analysis is required due to the trade-offs between these configurations' simplicity and intricacy.

This research is driven by the need to comprehend how the aforementioned configurations function in different scenarios and how their special qualities affect the more general goals of power quality, grid synchronisation, and system stability. This study attempts to connect theoretical expectations with real-world results through thorough simulations carried out in MATLAB Simulink, offering a grasp of the advantages and disadvantages of both arrangements. The research findings have implications for academia and industry, as they provide guidance for designing and implementing photovoltaic systems for maximum efficiency. Beyond the technical details, by providing insights into the real-world factors influencing decision-making, this study adds to the larger storey of sustainable energy integration which is especially necessary for developing Asian countries. The results of this study should direct PV technology developments, fostering the creation of robust and effective renewable energy systems, as the whole community works towards a more sustainable future free of pollution.

The work by Ciobotaru et al. (2005) compares two different control strategies for single stage PV inverters. Ostrem et al., (2006) studies a similar approach involving the application of a transformer to raise the inverter output voltage to the grid level. The inverter synchronises with the grid by means of a robust phase-locked loop (PLL). Chowdary and Shekhar (2014) studied the operation of a transformer operated by a sinusoidal pulse width modulation inverter with a focus on the iron losses in the transformer. Zhao et al. (2013) propose three dual mode boost buck-derived inverters with smooth transitions between modes. Prabaharan et al. (2015) propose a new asymmetric DC source hybrid multilevel inverter topology with minimised switch count with the possibility of achieving any number of levels. Faruqui et al. (2018) present a single-phase Z-source SPV inverter topology. A comparison between single-stage and dual stage systems is also depicted. Kumar et al. (2022) studied a multilevel single phase inverter topology. The approach uses a lower number of switches than conventional multi-level inverters. Islam et al. (2020) suggest a novel high frequency inverter with a reduced number of switches that are magnetically linked. The new topology is able to generate impressive results with a steep decrease in the number of switching devices. Babu et al. (2020) propose a novel single-stage cascaded differential boost single-phase PV inverter in a transformer-less configuration. Rakanov et al. (2020) studied a novel symmetric grid-tied transformerless inverter topology with a flying inductor. Chhabra et al. (2022) use indirect field-oriented control to study power electronic applications for grid integration of doubly fed induction machines. Seth et al. (2023) present a protection scheme for fault ride through a doubly fed induction generator. Varma et al. (2023) investigated modelling and control of induction machines.

Methodology

Single Stage Inverter System

The Foundation of the system is the Photovoltaic (PV) array, which is the primary source of solar energy. To ensure a precise representation of real operating conditions, the dynamic features of the PV array, such as temperature and irradiance dependence, are carefully simulated. In order to offer optimal power transfer by altering voltage levels as needed, an MPPT control algorithm is coupled between the PV array and inverter. Maximum and ideal power extraction from the panels is guaranteed by this controller. The voltage source inverter, which transforms the PV array's DC output into AC that can be supplied straight into the grid, is the centre of attention for the entire system. PV systems with high voltages must be taken into consideration in the single stage arrangement in order to meet the grid's voltage demand. To make sure the frequency, phase, and voltage of the inverter output meet the necessary parameters, the inverter is managed by the perturb and observe algorithm.

Integrating the inverter output into the grid is the system's last step. Following grid standards and guidelines, the inverter design guarantees a stable and seamless integration of solar power into the broader electrical system. In order to ensure grid compatibility, this phase includes grid synchronisation and addresses power quality issues. The simulation parameters provide a realistic picture of system dynamics in different conditions, taking into account environmental influences, load fluctuations, and inherent qualities of the PV array. The modulation index and frequency—two crucial control parameters in the inverter—are carefully chosen based on simulation findings as well as theoretical considerations.

The MATLAB Simulink simulation for the single stage setup involves an inverter subsystem as its centre piece. Four IGBT switches are arranged in the usual inverter configuration, controlled by four PWM signals. The frequency for PWM signals is 20 kilohertz. The DC input voltage to this inverter block is the output of the PV panel and hovers between values of 250V and 300V (Figure 4). This voltage level is comparable to that of the grid and hence can be utilisation for direct feeding into the inverter. The PV output is optimized for maximum power using an MPPT algorithm which is implemented as another subsystem in the simulation.

The PV characteristics are designed to simulate the real-world behaviour of a solar plant, this is done through the implementation of a variable irradiance whose plot can be seen in Figure 3. This addition of a variable parameter helps grasp the dynamic performance characteristics of the system. On the output side of the inverter, an inductor and capacitor are connected to simulate the line inductance and capacitance of the grid. Figure 1 represents the block diagram of a single stage PV voltage source inverter.

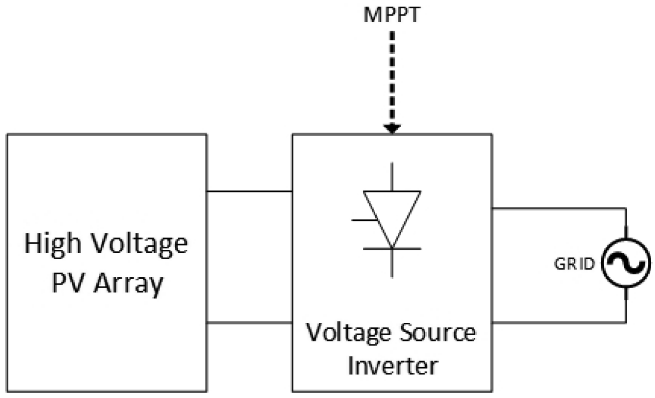

Figure 1: Single stage PV voltage source inverter system block diagram.

Dual Stage Inverter System

The two-stage inverter system adds another level of complexity to the single-stage setup, building on it to tackle the problem of low PV output voltage. In this setup, a boost converter with an MPPT control algorithm is used to direct the DC output of the PV array first. In order to provide an effective power transfer procedure, the boost converter dynamically ramps up the voltage to satisfy the requirements of the voltage source inverter that follows.

As for the simulation of the dual-stage inverter setup, to ensure consistency, the same inverter and PV array setups are used as the single-stage setup. The key difference lies in the intermediate stage of the boost converter in closed-loop configuration. The buck converter allows for the inverter systems to be used with commercially available, cheaper PV panels. The buck converter makes use of a single IGBT switch controlled by a PWM signal at 5 kilohertz frequency. The DC input voltage being fed into the boost converter in this simulation is the PV output which is the same as the single-stage configuration between 250-300V. This voltage is boosted up to 400V (Figure 7). This boosted voltage is then fed into the inverter. Hence the system operates in the two-stage configuration. Figure 2 represents the block diagram for two stage inverter topology.

The PV characteristics are designed to simulate the real-world behaviour of a solar plant, this is done through the implementation of a variable irradiance whose plot can be seen in Figure 3.

The parameters used for the design of the simulation environment are given in Table 1. The parameters have been chosen based on the chosen wattage level of the converter.

Results

Single-Stage Inverter System Performance

The inverter in the single stage system is operated using the Perturb and Observe algorithm. The readings below show the performance characteristics of the single stage configuration. The key insight from the observed metrics is the voltage levels of the PV panel. The output voltage is observed to have a significant variation as the parameters of the PV array change. This variation leads to an increase in the complexity of operation in terms of the control signal generation. Considering the hardware implementation, single stage setup would be more hardware intensive on the controller front. Figure 4 indicates the output waveform of the PV panel in single stage configuration. The output voltage

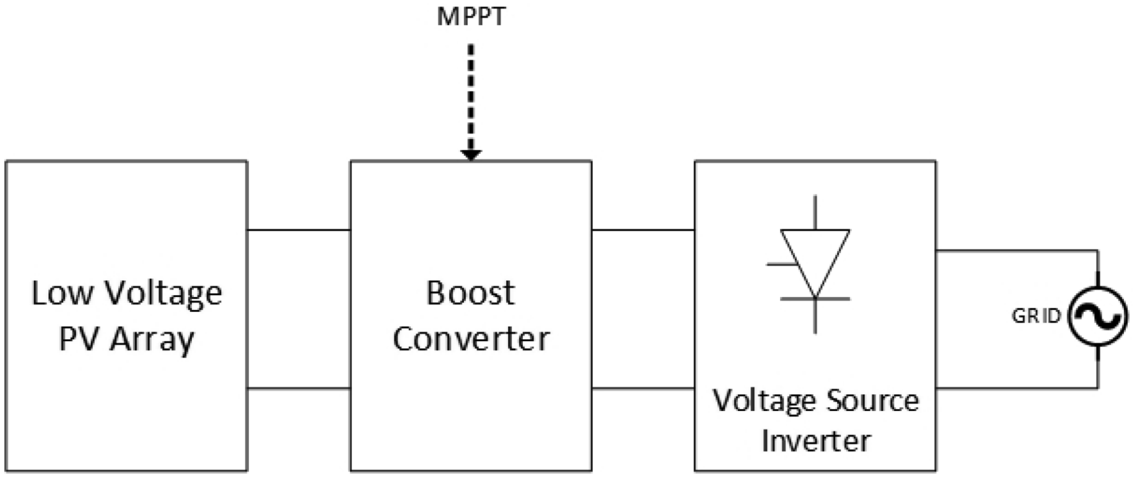

Figure 2: Dual stage PV voltage source inverter system block diagram.

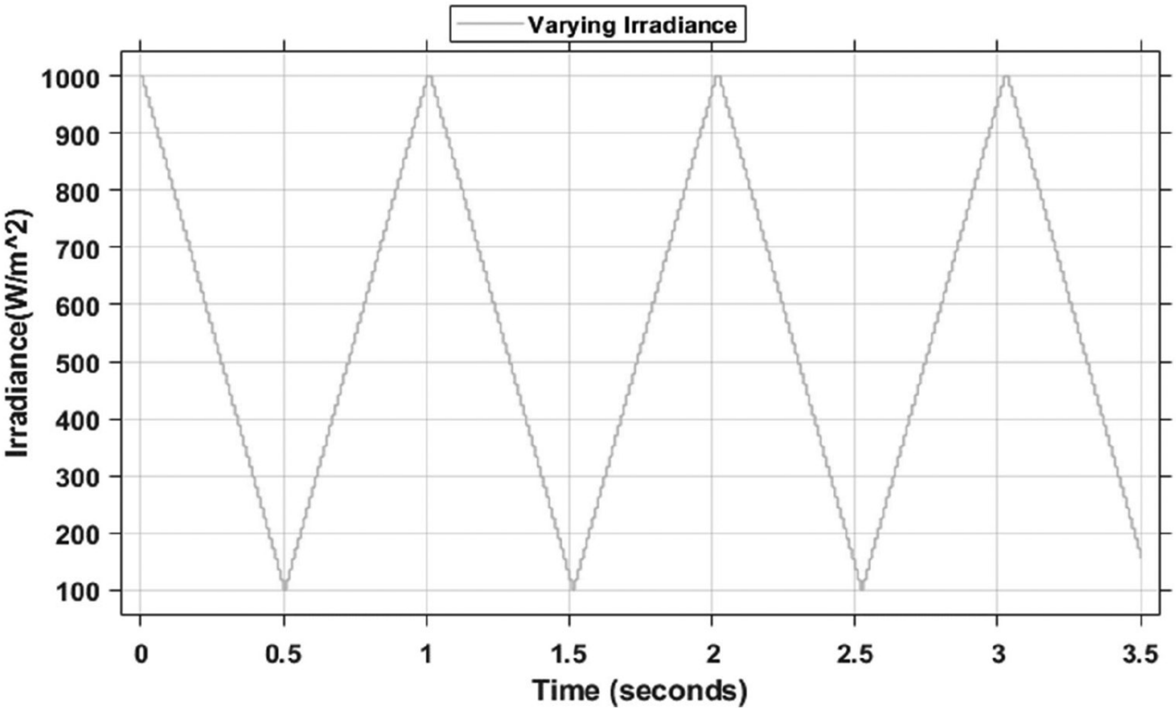

Figure 3: Variable curve implemented in the PV array parameters.

and current plots of the inverter (Figures 5 and 6) indicate proper function of the inverter with minimal transients and harmonics in the output waveforms.

Two-Stage Inverter System Performance

Comparatively, the addition of a boost converter and MPPT algorithm to the two-stage inverter system results in increased complexity. The PV array's low output voltage problem was effectively resolved by the boost converter, showcasing its flexibility in response to changing sun conditions. The stepped-up DC voltage was effectively converted to AC by the inverter, which was managed by the Perturb and Observe algorithm, in accordance with grid regulations. The two-stage system's adaptability was demonstrated by its ability to accommodate PV installations with lower output voltages. The single-stage configuration's constraints were overcome by the system, which resulted in increased power transfer efficiency. The voltage is boosted up to 400V as shown in Figure 7. The continual

Table 1: Parameters of associated system components

Component	*Parameter*	*Definition*
IGBT Switch	Internal resistance	10^{-4} Ω
	Snubber resistance	10^{4} Ω
	Voltage rating	1200 V
	Current rating	50A at 25°C and 25A at 100°C
	Maximum power rating	60 Kw
Grid	Inductance	4.5 mH
	Capacitance	6.23×10^{-6} F
PV Array	Module	Zytech Engineering Technology ZT190S
	Peak power	190.1592 W
	Open circuit voltage	44.86 V
	Short circuit current	5.5A

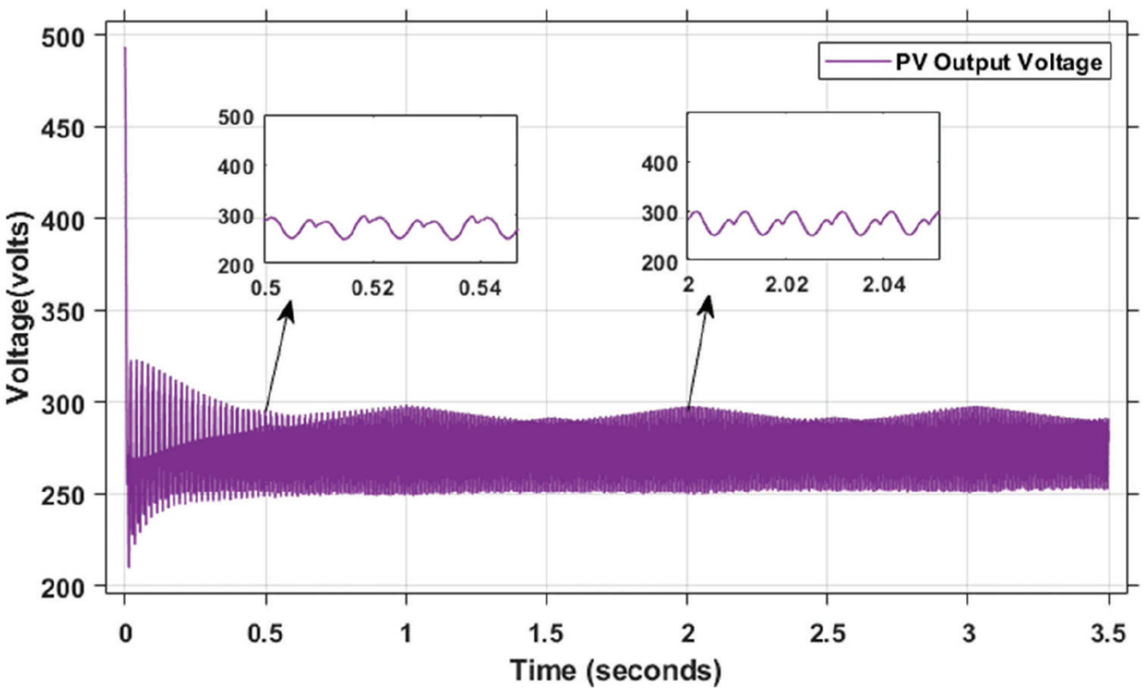

Figure 4: PV panel output voltage in single stage configuration.

fulfilment of grid synchronisation and power quality considerations demonstrates the two-stage inverter's compliance with grid standards. Figures 8 and 9 indicate the output voltage and current waveforms of the converter in two stage configuration.

Comparative Analysis

The key differences between the two systems can be analysed by stakeholders to ensure maximum efficiency. The first key difference between the setups is the complexity. The addition of a boost converter requires an additional DC-DC converter in the setup. The boost

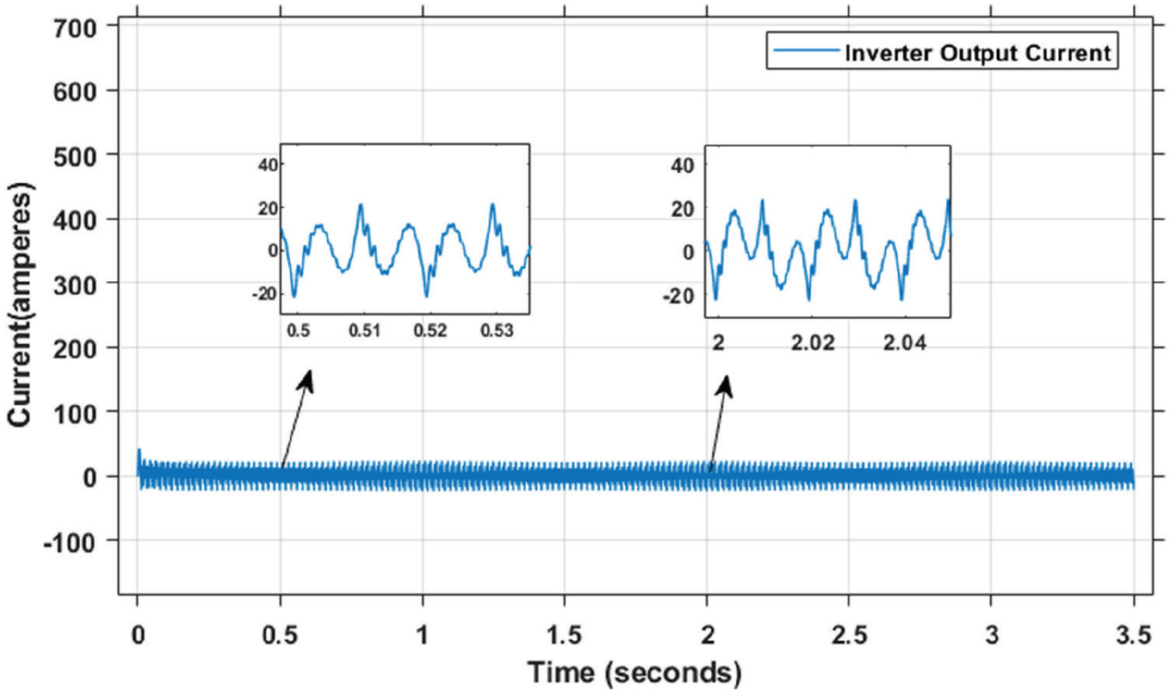

Figure 5: Voltage source inverter output current (single stage).

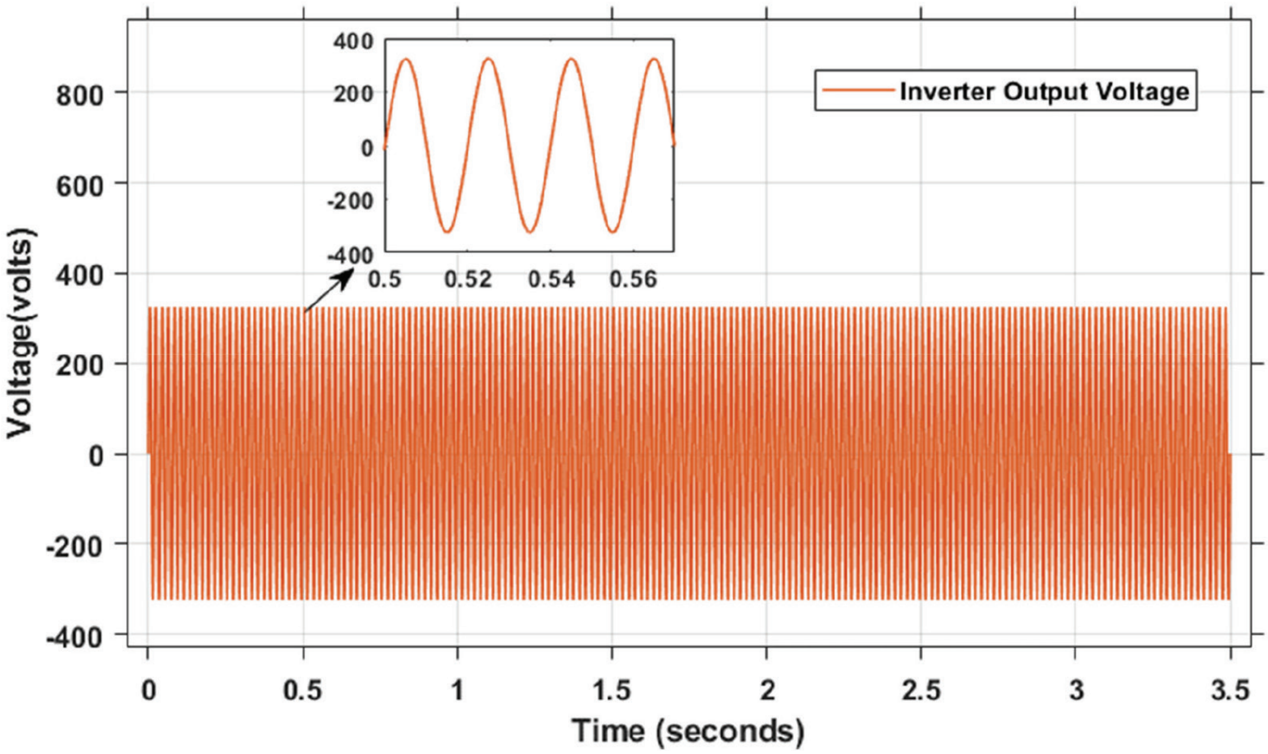

Figure 6: Voltage source inverter output voltage (single stage).

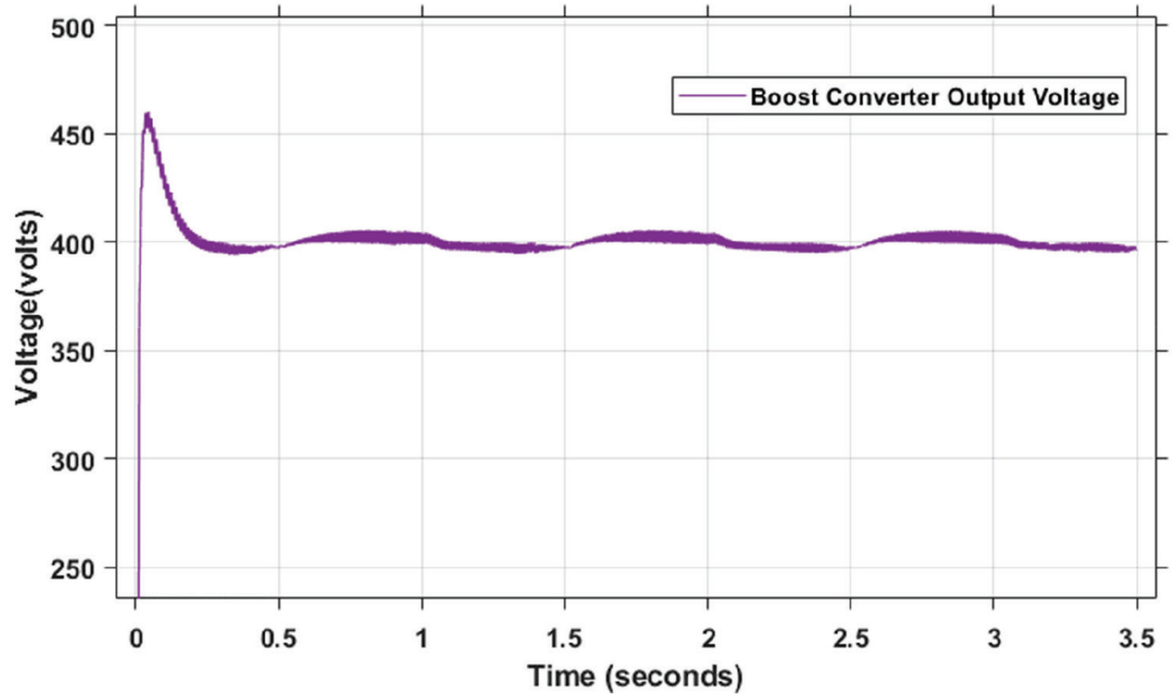

Figure 7: Boost converter output voltage in dual stage configuration.

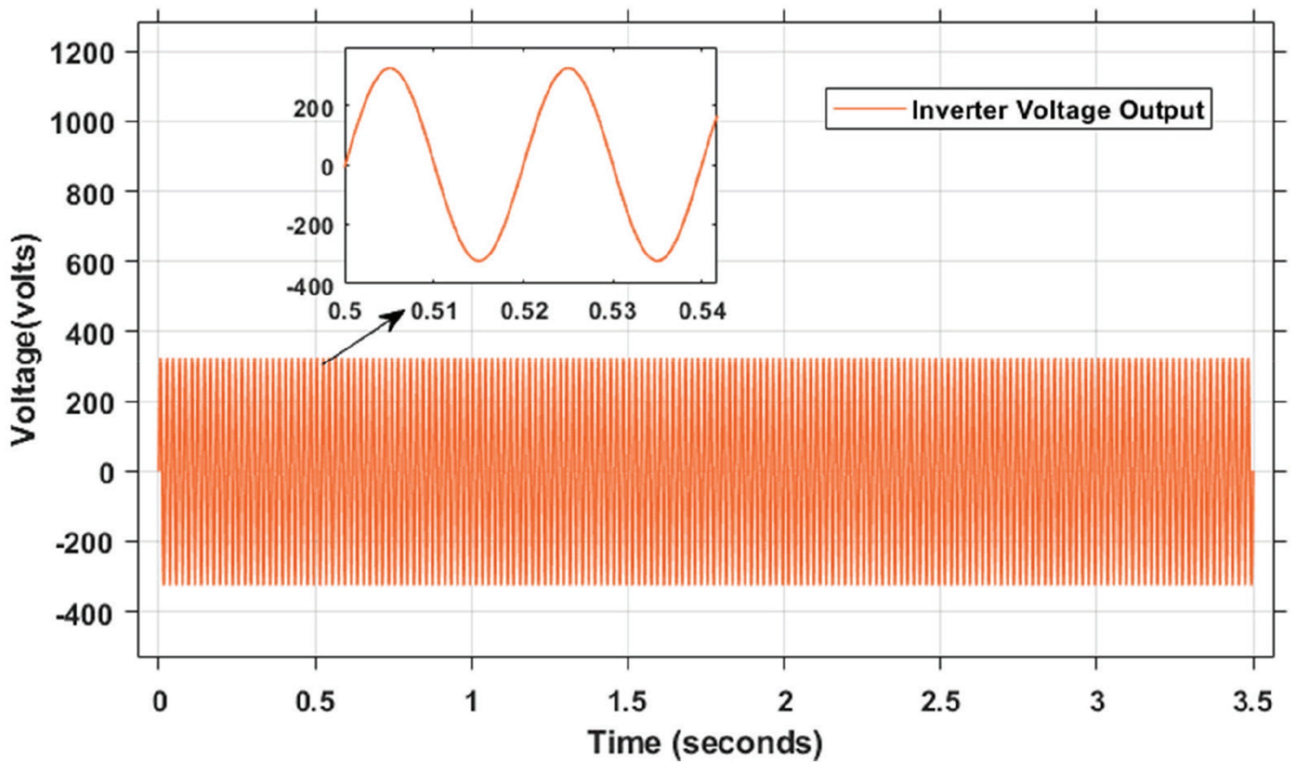

Figure 8: Voltage source inverter output voltage (dual stage).

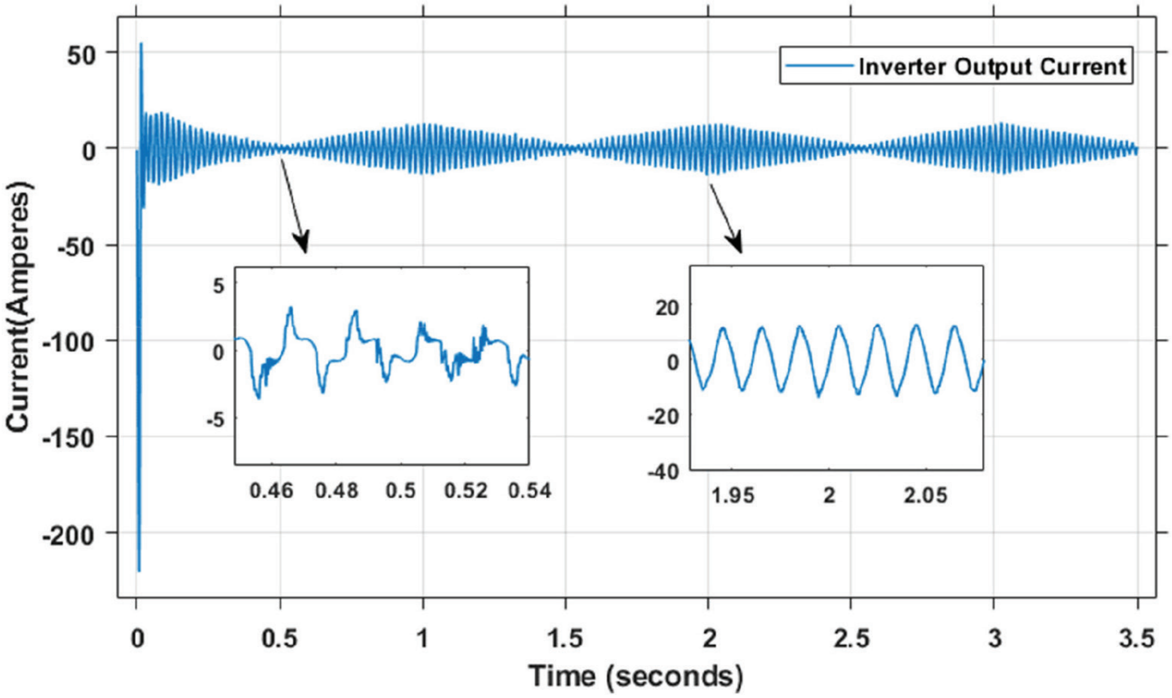

Figure 9: Voltage source inverter output current (dual stage).

converter adds a controlled switch to the system whose control would require additional control hardware as well, in addition to the control device having more processing power.

Another point of contrast between the two devices would be the cost. With the added hardware required for the boost converter, there will be a significant increase in the cost of the two-stage system. In the case of single-stage systems, the inverter setup would have reduced cost but the PV array would have a higher price since the panels for higher voltage generation have a higher cost. As for the control complexity, the dual-stage system has higher control complexity owing to the addition of a switch that operates at a different switching frequency. This increase in control complexity would result in higher costs and hardware requirements.

Another notable difference can be observed in the current curves of the two systems. In the single-stage configuration, there is less variation in the current values with the variation in PV characteristics while in the dual-stage system, a sharp decline in current values can be seen during periods of minimum irradiance.

The boost converter would also provide the facility required to upgrade the voltage levels in times when the PV array is producing lower voltages. This results in added flexibility for the system, allowing it to operate at times of low voltage or even for use in other systems with different PV characteristics and setups.

Implications and Future Directions

Our findings have ramifications that go beyond the specifics of this investigation. It becomes increasingly important to comprehend the subtle dynamics of various PV designs as the renewable energy environment changes. Future studies could look into hybrid systems, which combine the benefits of two- and single-stage solar installations to increase efficiency and adaptability even further.

Future work on PV panels is necessary as they are significant contenders in becoming the next big source of energy after fossil fuels. With rapid consumption, conventional energy sources are depleting and a crisis is imminent for humanity. Without proper ways to harness non-conventional sources, we would have to rely on whatever little energy would be available, creating instability in society.

This work offers a premise for further research work on the concepts of multistage inverters with various functional modifications such as transformer output and reduced number of switches. Such work would be greatly beneficial for the energy mission.

Discussion

The observed differences in performance between the single- and two-stage designs emphasise how crucial it is to take project-specific requirements into account. For high-voltage PV installations, the single-stage inverter system proved to be a simple and effective solution, exhibiting excellent stability and grid synchronisation. Its inability to support lower output voltages, however, became evident, indicating a trade-off between simplicity and versatility. On the other hand, the two-stage inverter system showed improved flexibility by adding a boost converter to solve the problem of low output voltage. This arrangement demonstrated exceptional adaptability under a range of solar conditions, indicating that it is a viable option for installations with a variety of PV features. Performance concerns are a topic of discussion that highlights the necessity of a customised strategy that matches the selected design to the unique needs of the photovoltaic system.

Efficiency became apparent as a critical parameter for assessing the inverter topologies' efficacy. By optimising power transfer through the boost converter, the two-stage system demonstrated considerable efficiency increases even with its additional components. This discovery bears noteworthy consequences for undertakings wherever efficacy is of utmost importance. The talk highlights how the two-stage system can improve overall system efficiency and presents a strong substitute for the single-stage configuration's ease of use. A key point of our discussion is the two-stage inverter system's flexibility in responding to changing solar circumstances and lower output voltages. This flexibility overcomes a drawback of the one-stage arrangement and increases the two-stage configuration's usefulness. The two-stage technology proved to be a viable integration option for bigger electrical infrastructures by continuously upholding grid compatibility and power quality standards.

In selecting an inverter arrangement, there are inherent trade-offs between simplicity and versatility, as the discussion highlights. Stakeholders and project developers need to carefully consider these trade-offs in light of the unique features of the PV installation. The single stage system offers simplicity and reduced cost with the downside of the requirement of a high voltage PV array. Dual-stage systems eliminate the need for high voltage PV arrays at the cost of simplicity. The decision-making process entails a detailed assessment of the project's needs, taking into account variables including output voltage requirements, solar situation variability, and overall efficiency targets. Even though the study offers insightful information, it is important to recognise its limits. The simulations might not accurately reflect the complexity of real-world situations since they are predicated on certain assumptions and idealised circumstances. Future research attempts may examine hybrid configurations or use more complex control algorithms to further optimise the performance of PV systems. One major area where further work can be done is the increased variance of different characteristics of the PV array.

To summarize, a single stage system would be beneficial in a system where high-voltage PV panels have been installed or several low voltage panels have been connected in series for low power applications unlike grid integration, due to the current limit. The single stage system would thus be cost and space-effective, providing a simple solution for the requirement.

As for dual stage systems, they are applicable in scenarios where PV systems have lower output voltages. The DC-DC boost converter, being a constant power device would provide precise control and produce a cleaner current curve. Hence, dual stage systems have better control capabilities and adaptability and would benefit lower voltage systems making them the correct choice to use with conventional PV panels such as those that produce 12V output.

Conclusion

In the pursuit of expanding renewable energy solutions, this comparative study has comprehensively compared the performance and the characteristics of single-stage and two-stage single-phase PV voltage source inverter systems. The results highlight how crucial it is to match the chosen inverter design to the particular needs of the photovoltaic (PV) system as well as the overall goals of the project. For high-voltage PV installations, the single-stage inverter system excelled in stability and grid synchronisation due to its simplicity and efficiency. Its inability to support lower output voltages, however, highlights the compromises that come with simplicity.

In contrast, the two-stage inverter system's MPPT algorithm and boost converter added yet another level of complexity. This intricacy helped to overcome the problem of low PV output voltage and improved the system's capacity to adjust to changing solar conditions. The two-stage arrangement proved to be more adaptable and efficient, offering a viable option for a range of PV systems.

The two-stage system's efficiency benefits demonstrate its potential for optimising power transfer, defying the widely held belief that more complexity inevitably impairs overall performance. The two-stage system has made a significant contribution to the changing field of photovoltaic technology with its flexibility in responding to changing solar conditions and its capacity to handle lower output voltages. Stakeholders have to carefully consider the trade-offs between simplicity and adaptability when making decisions because each PV installation is different. The study's conclusions not only offer useful information for ongoing initiatives but also lay the groundwork for upcoming breakthroughs and developments in PV inverter design.

The integration of PV technologies into the grid can be beneficial in the current scenario where decentralised energy systems are being developed. Solar energy is especially beneficial for rural areas where grid expansion is uneconomical. Solar conversion systems help harness an abundant energy resource and pollution-free. Environmentally, there are several benefits of such systems and their adoption is necessary, especially for solar-rich third-world Asian countries.

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